TOPEX /POSEI DON Ml SS1 ON EARLY RESUI .TS

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Abstract

The joint U.S/France TOPEX/Poseidon satellite was launched on August 10, 1992. Orbiting at an altitude of 1336 km with an inclination of 66 degrees, the satellite has been measuring the global sea surface height using a radar altimeter system along the same tracks on Earth every 10 days since late September, 1992. The major goal of the mission is to make precise measurements of the height of the sea surface for the study of the dynamics of large-scale ocean circulation. Additionally, the data will be used for studying ocean tides and marine geophysics. The radar altimeter also measures wave height. and wind speed. The mission is being conducted to optimize the sea surface height. measurements for a minimum of three years. The primary objective of the first six months of the mission was to calibrate and validate the mission's measurements, This verification phase was completed at the end of February, 1993. The verification results indicate that all the measurement objectives have been met.. In fact, many measurements have exceeded performance requirements . The root-mean--square accuracy of the sea surface height. measurement is estimated to be about 5.7 cm, significantly less than the specification of 13.4 cm. A brief summary of the mission's characteristics as well as early results are presented in the paper.

Introduction

TOPEX/POSEIDON is a satellite mission jointly conducted by the United States' National Aeronautics and Space Administration and the France's Centre National d'Etudes Spatiales. The objective of the mission is to use a radar altimeter system to measure the height of the sea surface, which reveals the topography of the oceans, for the study of the circulation of the world's oceans. The measurement will also be used for the study of ocean tides and marine geodesy and geophysics. The radar altimeter also measures the wind speed and wave height along its nadir track.

The global change of our planet, the Earth, is a well recognized problem. The ocean, through its interaction with the Earth's atmosphere, biosphere and cryosphere, plays an important role in regulating the change of the Earth as a system. For instance, the potentially severe contrasts in climate between the poles and equator are greatly ameliorated by the presence of the ocean because of its large heat capacity and its contribution to the movement of heat from the equator to the poles. Much of the weather we experience is spawned over the ocean trough complex air-sea transfer processes. The important global fishing grounds are limited to small geographical areas dominated by special oceanic flows in response to the prevailing winds. The mixing and transport of chemical tracers and pollutants in the sea also affects the Earth system in a profound way. For example, the rate at which the burning of fossil fuel causes the temperature of the air to rise, the famous Greenhouse Effect, is determined to a large extent by the rate at which the ocean is able to absorb the CO_2 and by the rate at which the ocean warms due to increased atmosphere c heating]

Yet much about, the ocean is poorly understood, largely because the ocean is so difficult to observe. It is a global fluid with fluctuations occurring over a wide range of spatial and temporal scales. Only satellite systems have the potential for providing the data necessary to

~}'reject, Scientist, Earth and Space Sciences Division understand the oceans as a whole. TOPEX/POSEIDON is designed specifically for the study of the global ocean circulation and its variabilities by measuring the global sea surface height for a minimum of 3 years.

The utility of a satellite altimeter system for ocean circulation studies has been demonstrated by three previous missions: GEOS-3[2], Seasat[3] and Geosat[4]. However, none of these missions were optimally designed for ocean circulation studies, especially for ocean variabilities at the basin-wide scales that are most difficult to observe using ship observations. Given this shortcoming, TOPEX/POSEIDON was specifically designed for observing the large-scale ocean circulation with unprecedented accuracy[5]. The results from the mission are anticipated to make significant contributions to the knowledge of ocean circulation and its interaction with the atmosphere.

The TOPEX/POSEIDON satellite was launched by an Ariane 4 rocket from the European Space Agencyts Guiana Space Center in French Guiana, on August 10, 1992. Orbiting at. an altitude of 1336 km with an inclination of 66 degrees, the satellite has been measuring the global sea surface height, using a radar altimeter system along the same tracks on Earth every 10 days since late September, 1992, after a 42 day period of engineering check--out, and orbit. adjustments. Described in the following sections are the mission's characteristics and some early results.

Mission Description

Scientific Objectives

The primary scientific objective of the mission is a substantial increase in our understanding of global ocean dynamics by making precise and accurate observations of sea level for a minimum of 3 years. These observations will lead to the following: determination of the general circulation of the ocean and its variability; a test of the ability to compute circulation that results from forcing by winds; a description of the nature of ocean dynamics; calculation of the transport of heat, mass, nutrients, and salt by the oceans; determination of the geocentric ocean tides; an investigation of the interaction of currents with waves. The sea-level observations will also make contributions to marine geophysics leading to improvement in the knowledge of the marine geoid and increased understanding of lithospheric and mantle processes.

Instruments and Satellite

There are six science instruments in the mission payload (Figure 1), four provided by NASA and two by CNES. They are divided into operational and experimental sensors as follows:

(1) Operational Sensors

(a) Dual-Frequency Radar Altimeter (ALT) (NASA).
(b) TOPEX Microwave Radiometer (TMR) (NASA).
(c) Laser Retroreflector Array (LRA) (NASA).
(d) Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Tracking System Receiver (CNES).

(2 Experimental Sensors

(a) Single-Frequency Solid-State Radar Altimeter (SSALT) (CNES) .
(b) Global Positioning System Demonstration Receiver (GPSDR) (NASA) .

The ALT, operating at 13.6 GHz (Ku band) and 5.3 GHz (C band) simultaneously, is the primary instrument for the mission. The measurements made at the two frequency channels are combined to obtain precise altimeter height that is free from errors caused by ionospheric free electrons, of which the total content is obtained as a by--product. of the measurements. This altimeter is the first. one that utilizes two-channel measurernents for ionospheric range corrections.

The TMR uses the measurement of sea-surface microwave brightness temperature at three frequencies (18 GHz,21 GHz, and 37 GHz) to estimate the total water-vapor content in the atmosphere; this estimate is used to correct, errors in the altimeter measurement that result from this source. The 21-GHz channel is the primary channel for water- vapor measurement, . The 18- GHz and 37- GHz channels are used to remove the effects of wind speed and cloud cover, respectively, in the water-vapor measurement.

The LRA is used with a network of 20-25 satellite laser ranging stations to provide the baseline tracking data for precision orbit. determination and calibration of the radar altimeter bias. The DORIS tracking system provides an alternate set of tracking data using microwave Doppler techniques for precision orbit-determination. The DORIS system was first demonstrated by the SPOT-2 Mission. The system is composed of an onboard receiver and a network of 40-50 ground transmitting stations, providing all-weather, global tracking of the satellite. The signals are transmitted at. two frequencies (401.25 MHz and 2036.25 MHz) to allow the removal of the effect-s of the ionospheric free electrons in the tracking data. Therefore, the total content of the ionospheric free electrons can also be estimated from the DORIS data and used for the ionospheric correction for the SSALT.

The two experimental instruments are intended to demonstrate new technology. The GPSDR, operating at 1227.6 MHz and 1575.4 MHz, uses a new technique of GPS differential ranging for precise, continuous tracking of the spacecraft with an accuracy of a few centimeters. The SSALT, operating at a single frequency of 13.65 GHz, has validated the technology of a low-power, low-weight, altimeter for future Earth-observing missions. It. shares the same antenna with the ALT. The SSALT has been operating for approximately 10 % of the time.

The TOPEX/POSEIDON satellite was built by Fairchild Space as an adaptation of the Multi-Mission Modular Spacecraft (MMS), which had successfully carried payloads including the Solar Maximum Mission in 1980, the Landsat-4 in 198?, the Landsat-5

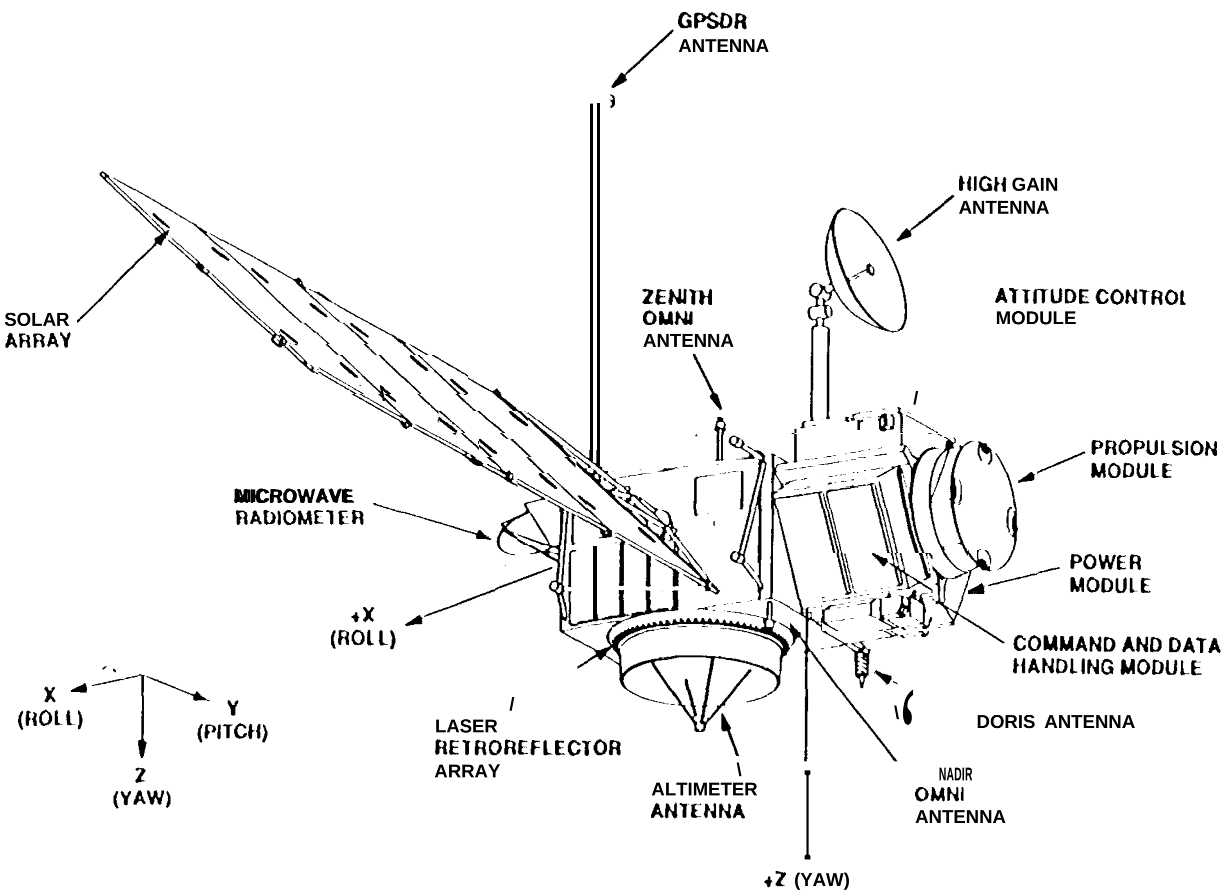

Figure 1. The TOPEX/Poseidon satellite and its payload in the fully-deployed configuration in orbit. The flight direction points to the positive X-axis.

in 1984. The MMS design was modified to meet the TOPEX/POSEIDON requirements. The satellite! bus consist-s of the MMS and the Instrument Module. Shown in Figure 1 is the fully deployed TOPEX/POSEIDON satellite featuring the major modules, sensors, and antennas.

Orbit Configuration and Determination

lobe satellite is flying in a circular orbit at an altitude of 1336 km with an inclination of 66 degrees and a repeat period of 10 days. The repeatability of the ground tracks has been maintained within +/- 1 km. This orbit. configuration is chosen to maximize the science return of the mission with considerations of the requirements imposed by sampling, orbit. determination, and the avoidance of tidal aliasing.

The satellite orbit tracking provided by the laser ranging and DORIS is not continuous in time. Orbit computation based on dynamical equations and the tracking data is required to produce a continuous, precise orbit for the mission. Precision orbit determination teams have been established by both NASA and CNES to accomplish this task. Because orbit error is the most. significant error source for the sea-level measurement, a long--lead prelaunch effort has been made by these teams to develop a much improved model for the Earth's gravity field to be used for the orbit determination. A hierarchy of progressively improved models has been p~-educed by this effort 6-7. After the launch of the satellite, these teams have used the satellite tracking data to further "tune" the gravity model to optimize it for the mission.

Scientific Investigations

Science investigations using the unique capabilities of TOPEX/Poseidon are being carried out by the members of the Science Working Team - 38 Principal Investigators selected by NASA and CNES through the process of Announcement of Opportunity. The selection was made based on the scientific merit of the proposed investigations and their relevance to the mission's scientific objectives. While the Principal Investigators do not have any exclusive use of the data produced by the mission, they are expected to deliver the main scientific results from the mission. There are 16 Principal Investigators from the United States, 13 from France, from Japan, 2 from Australia, anti one from each of the following countries: United Kingdom, South Africa, West Germany, Norway, and the Netherlands. Summaries of the individual investigations can be found in mission's Science Plan [5].

Management

The Jet Propulsion Laboratory of the California Institute of Technology, under a contract with NASA, has the responsibility of project management for the TOPEX/POSEIDON Mission. 'l'his responsibility includes mission planning and control, acquisition of the satellite, development and acquisition of the NASA sensors, design and development of the NASA ground data system, and control of the system interfaces. Within CNES, Centre Spatial de Toulouse (CST) is responsible for the Ariane launch-vehicle system and the Ariane space launch services, participation in mission design, management, and development of the CNES sensors, and development of the CNES ground data system. Mission operations are conducted at JPL with data processing to produce the baseline science data (the GDR) at, both JPL and CST.

Early Mission Results

Measurement Performance

During 22-25 February 1993 a verification workshop was conducted at the Jet, propulsion-l Laboratory in Pasadena, California. The meeting was held at the conclusion of a focused six month verification phase jointly conducted by NASA and CNES. The NASA verification effort was centered around Harvest Platform off Point conception, California; the CNES effort. was conducted around the Lampedusa island in the Mediterranean Sea. Over 150 scientists anti engineers participated in the workshop to evaluate of the mission's performance. A preliminary error budget. for the sea surface height, measurement versus the mission's requirement is shown in Table 1. The root-mean-square accuracy of a single pass measurement averaged over 3 seconds (about 20 km along track) is 5.7 cm, significantly less than the mission's requirement of 13.4 cm. 'l'he reader is referred to the verification workshop report. [8] for details of the background information this orbit accuracy repor Led in the workshop was 8 cm based on the prelaunch gravit y model . After 1 aunch, the various satellite tracking data were used to derive an improved gravity model, which yielded the 4.7 cm accuracy reported in Table 1.

11'stile 1. A Preliminary Assessment of TOPEX/Poseidon Measurement Accuracies (one sigma values in cm)

	Performance	Requirement
ALTIMETER RANGE		
Altimeter noise[1]	1.4	2.0
EM bias	2.0	2.0
Skewness [2] "	1.4	1.0
1 onosphere [3]	0."/	2.2
Dry Troposphere	0."/	0.7
Wet Troposphere	1.5	1.2
TOTAL ALTIMETER RANGE [4]	3.3	4,0
RADI Al , ORBI T HEI GHT [5]	4.7	12.8
S1 NGI .E PASS SEA HEIGHT	5. "1	13.4

Notes-
(1) Al timeter noi se is based on 3-see average and significant wave height (SWH) = 2 m.
(2) Not, well determined for SSALT
(3) Usc 2.0 cm for' DORIS-based correct ion
(4) Altimeter bias and bias drift not i ncluded
(5) Post verification workshop estimate based on the JGM-2 gravity model

Shown in Figure 2 is the evolution of the measurement accuracy of satellite alt ime try over the past 1 5 years. The unprecedented accuracy of TOPEX/Posei don has for the first time allowed the scientist. s to be able to detect the weak, large-scale ocean vari ability that is characterized by the horizontal line of 15 cm in the figure.

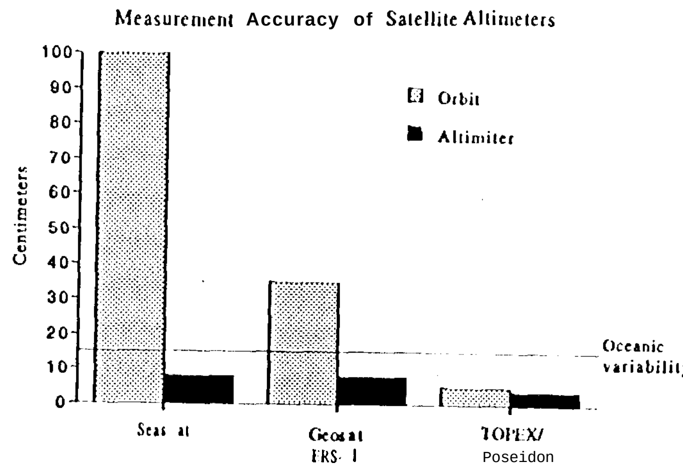

Figure 2. Evolution of the accuracy of sea surface height. measurement by satellite altimeters.

Ocean Topography

Shown in Figure 3 is a map of ocean topography produced from 200 days' worth of data collected by the mission from October, 1992 to April, 1993. Ocean topography is a measure of sea level relative to the Earth's geoid, a surface on which the gravity field is uniform. Oceanographers use ocean topography maps to calculate the speed and direction of ocean currents the same way meteorologists use maps of atmospheric pressure to calculate the speed and direction of wi nds. TOPEX/Poseidon is the first space mission that allows scientists to map ocean topography with sufficient accuracy to study the large-scale current systems of the world's oceans. The total relief of ocean topography shown in this map is about two meters. The maximum elevation is located in the western Pacific Ocean and the minimum is around Antarctica. In the Northern Hemi sphere, ocean currents flow clockwise around the highs of ocean topography and counterclockwise around the lows. This process is reversed in the southern' hemisphere. The major current systems of the world's oceans such as Kuroshio (the current south of Japan), Gulf Stream, and the Antarctic Circumpolar Current, among others, are clearly visible in the map. These highs and lows are the oceani c counterparts of at. mospheri c

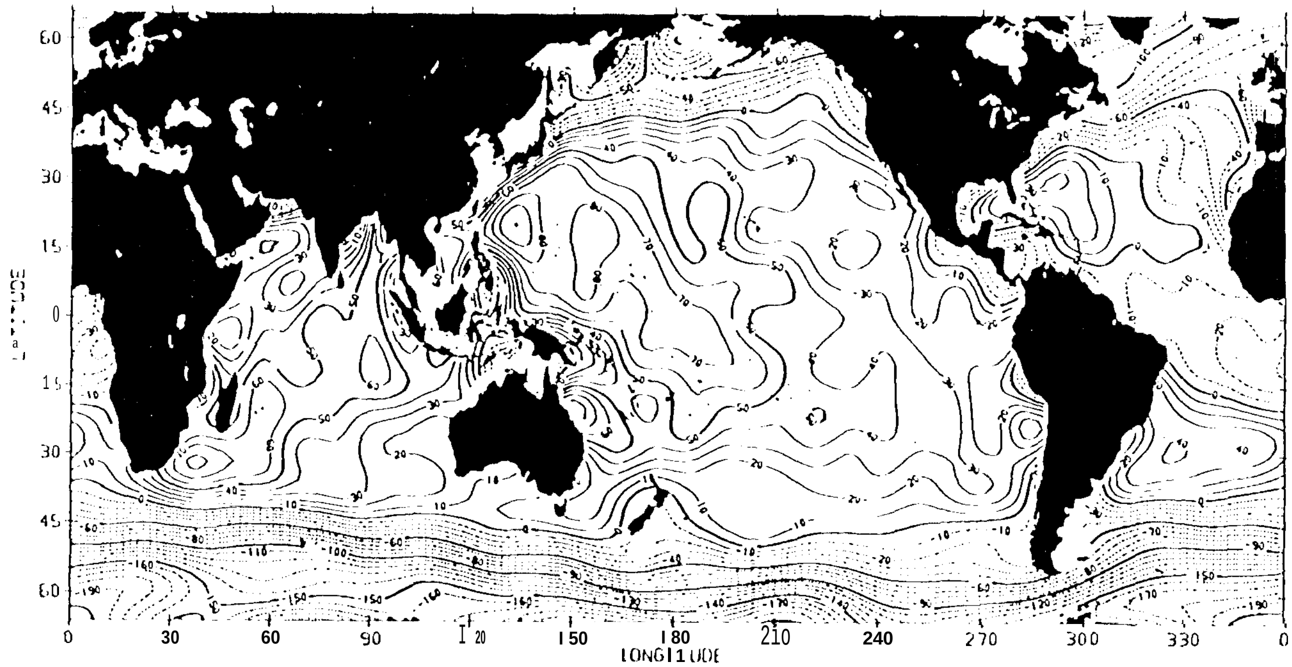

Figure 3. Ocean dynamic topography calculated from 200 days' worth of data (October 1992 - April 1993; Cycle 21 was not used) . Expansion up to spherical harmonics degree and order 20 (with wavelengths shorter than 2000 km filtered out_). The geoid model used is JGM-2, the post-launch model tuned using satellite tracking data. Contour interval is 10 cm, with negative values cent.oul-ed in dashed lines. The data used are interim GDR with empirical orbit corrections applied.

calculation systems. The existence and basic structure of these ocean systems are constant, but the details of these systems are constantly Changing. Therefore, these features can be considered the "climate" of the ocean. Through the enormous amount of heat transported by the large-scale circulation systems revealed by the map, the ocean plays a fundamental role in maintaining the current habitable climate on Earth. Understanding the dynamics of ocean circulation and its role in climate change is the main goal of the TOPEX /Poseidon Mission.

Sea Level Change

Figure 4 shows the change in sea level from the first 10 days of October, 1992 to the last 10 days of March, 1993, spanning a period of almost 6 months. The sea level change over this six month period is a combination of the effects of seasonal warming/cooling and wind forcing. In the Northern Hemisphere, the sea level in the Gulf Stream (off the U.S. east coast) arid Kuroshio (east of Japan) regions dropped by more than 30 cm. Most of this drop was caused by the winter cooling of the ocean by the cold continental air mass blown off the North American and Asian continents. Sea level rise of 5-10 cm occurred at similar latitudes (30-40 degrees) in the Southern Hemisphere, result. ing from the warming by the summer atmosphere. It takes an increase (cic!c~-ease?) of 1 degree Celsius in the average temperature of a water column 50 meters deep to cause the sea level rise (fall) by 1 centimeter. Note that. the sea level change in the Norther Hemisphere is larger than that. in the Southern Hemisphere. This is caused by the larger land mass of the Northern Hemisphere that. creates colder winter continental air mass that- cools the ocean water off the east coasts of the continents at. temperate lat. itudes.

The sea level drop just north of the equator in both the Pacific anti the Atlantic Oceans was caused by the seasonal deceleration of the Equatorial Counter Currents resulting from the seasonal change in the trade winds. The sea level rise in the eastern tropical Pacific Ocean off the coast of South America was the remnant of the Kelvin wave pulses generated in last December. A Kelvin wave

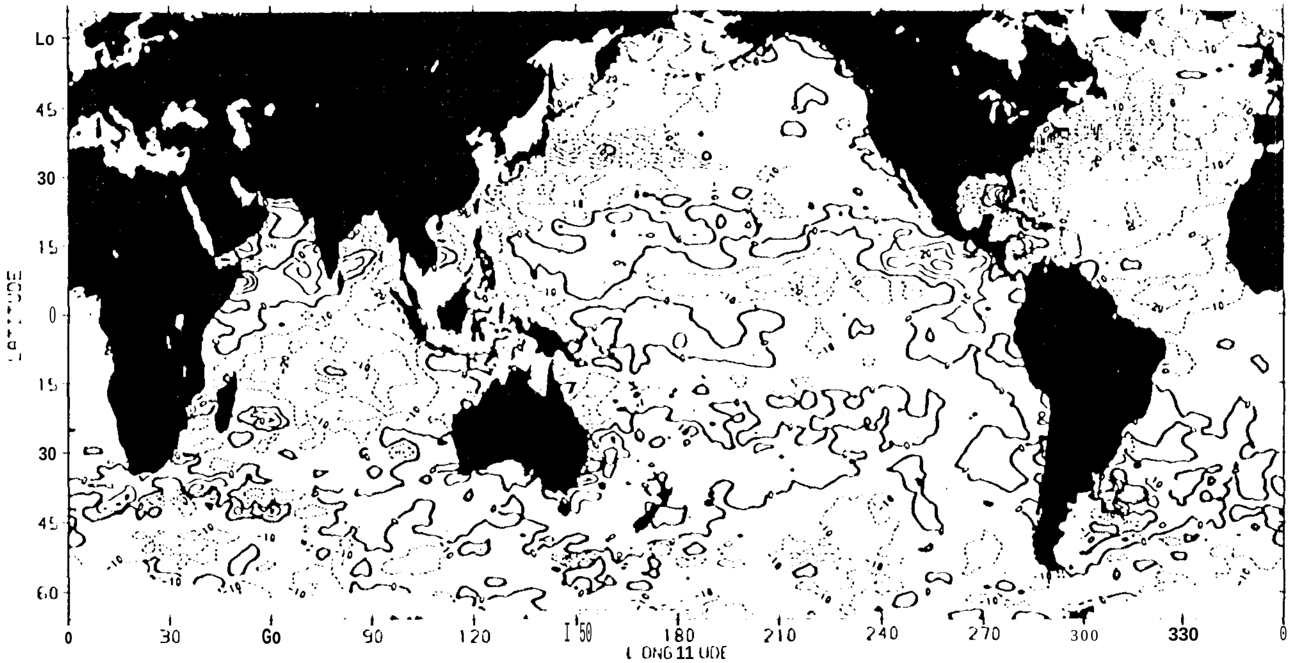

Figure 4. Global sea level change from early October, 1992 (Cycle 2) to late March, 1993 (Cycle 19). Positive values (solid contours) indicate sea level rise; negative values (dashed contours) indicate sea level fall. Contour interval is 10 cm, with negative values contoured in dashed lines. The data used are interim GDR with empirical orbit corrections applied.

pulse creates a surge of warm water propagating eastward along the equator and can contribute to El Nino conditions.

The sea level change in the Indian Ocean is characterized as a fall in the eastern and the southern regions and a rise in the northwestern region. This is a response of the ocean to the seasonal cycle of the monsoon winds.

Data Products

The baseline data products from the mission are the Geophysical Data Record (GDR). The algorithms for producing the data have been fine-tuned according to the results of the verification workshop. The GDR's are being distributed by both NASA's Physical Oceanography Distributed Active Archive Center (PO-DAAC) at JPL and France's AVISO at Toulouse. These data are available to the international science community via magnetic tapes and CD-ROMs upon request to the two data centers. The GDR's are available for distribution roughly two months after data reception. Interim data of lesser quality (10-15 cm accuracy) are available for operational applications via electronic access to the PO-DAAC's computer system. Users of the interim data products include the U.S. NOAA and the Japanese Meteorological Agency.

Conclusions

Early results from the TOPEX/Poseidon Mission have indicated that the accuracies of the mission's measurements have exceeded requirements. The GDR's have been produced and distributed to the Principal Investigators on a routine basis. The data are also available to the international science community for research use. Three to five years' worth of data of the high quality indicated in the paper are anticipated to make major advancement in our knowledge of the circulation of the world's oceans.

Acknowledgements

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